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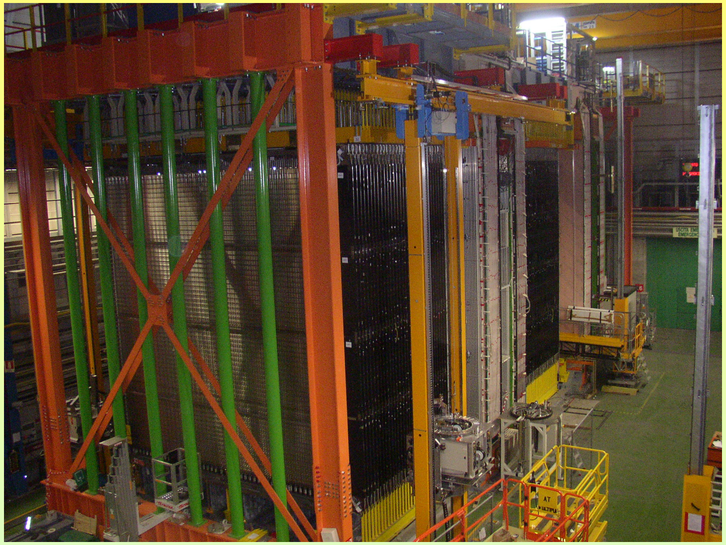


Observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation with OPERA

On behalf of the OPERA Collaboration

S.Dusini - INFN Padova

INFN Sezione di Padova

NEUTRINO2014
XXVI International Conference on Neutrino Physics and Astrophysics
June 2-7, 2014, Boston, U.S.A.

OPERA

Neutrino appearance

Neutrino oscillation pioneered via neutrino disappearance
Super-KAMIOKANDE, MACRO….
…and for long time the disappearance dominated the scene
SK, SNO, MINOS, KamLAND, Borexino….

Hard life for appearance:

Solar scale:

$\nu_e \rightarrow \nu_\mu$: below threshold for μ production

Atmospheric scale: experimentally difficult

$\nu_\mu \rightarrow \nu_e$: subleading (T2K)

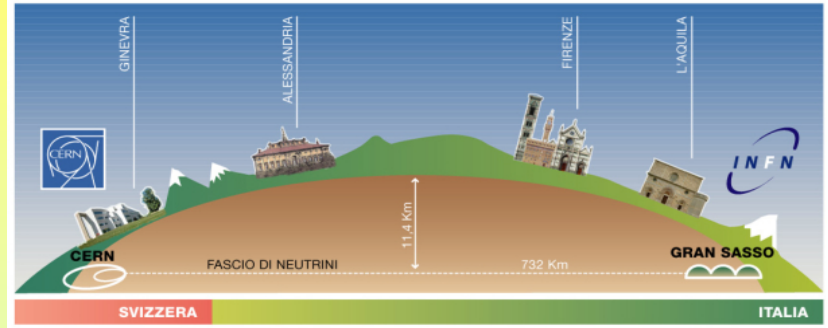
$\nu_\mu \rightarrow \nu_\tau$: with cosmic ray neutrinos (SK) statistical separation from large background

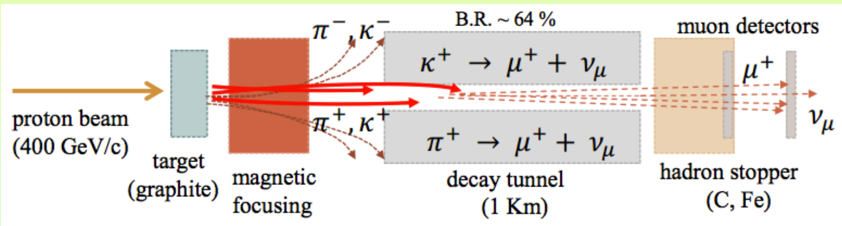
$\nu_\mu \rightarrow \nu_\tau$: LBL beam neutrinos (OPERA) with tau lepton identification on an event by event basis

The neutrino appearance is a key observation to establish the neutrino oscillation phenomenon.

CNGS beam

Beam requirements
1) high neutrino energy,
2) long baseline,
3) high beam intensity,

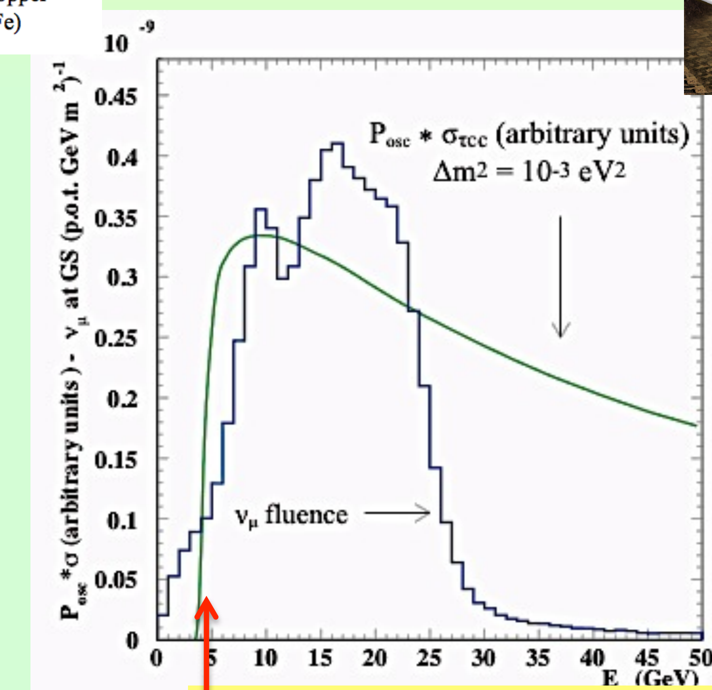




732 km

$$< E_{\nu_\tau} > \sim 17\ \mathrm{GeV}$$

$$\frac{L}{< E_{\nu_\tau} >} \sim 43\ \mathrm{Km/GeV}$$



High energy beam optimized to maximize tau production

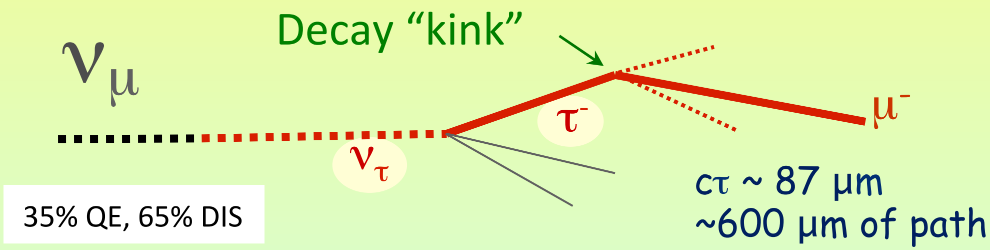
$P(\nu_\mu \rightarrow \nu_\tau) \sim O(1)\%$

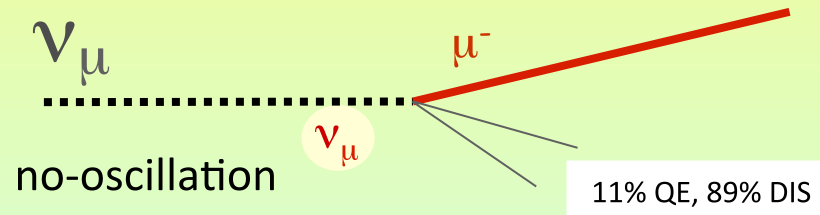
tau production threshold $E_\nu \sim 3.5$ GeV

τ detection $\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \to \tau^- + X$

The separation of the $\nu_\tau\, CC$ from the dominant ν_μ interactions

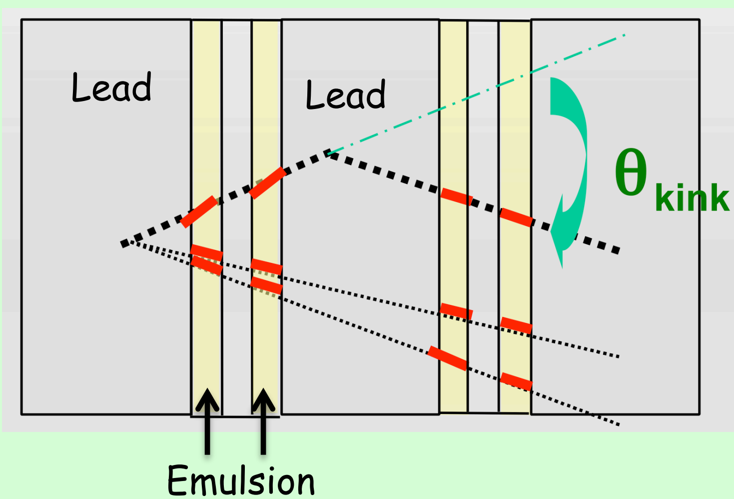
event-by-event, of the peculiar decay topology of the τ.



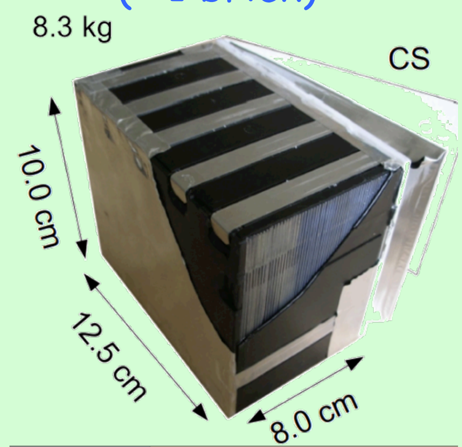


Hybrid detector

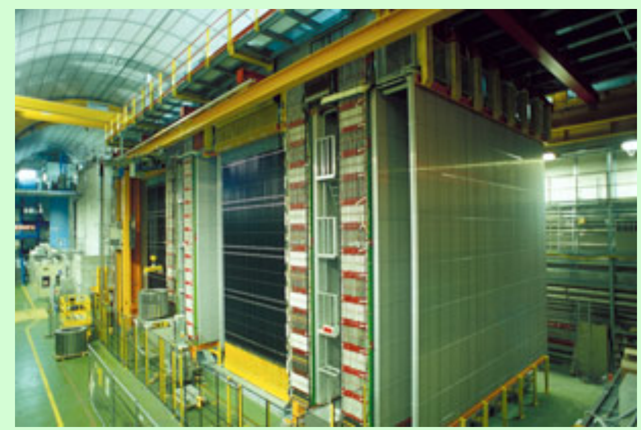
micrometric resolution



Emulsion Cloud Chamber
(= 1 brick)

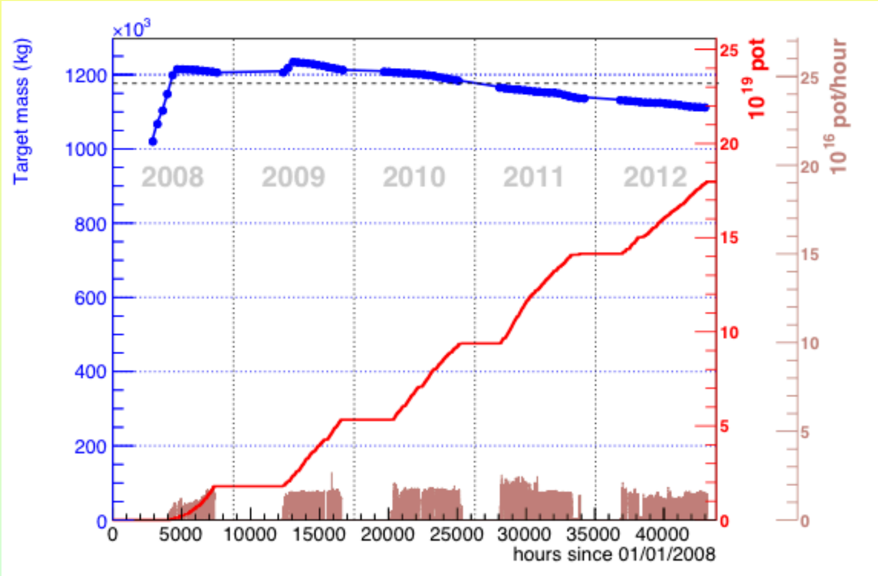


~150000 bricks (1.25 kton) +
electronic detectors



Collected data and status of the analysis

Year	P.O.T. (10^{19})	SPS Eff.	Beam days	ν interactions
2008	1.7	61%	123	1931
2009	3.53	73%	155	4005
2010	4.09	80%	187	4515
2011	4.75	79%	243	5131
2012	3.86	82%	257	3923
Total	17.97	77%	965	19505



→ 80% of the design

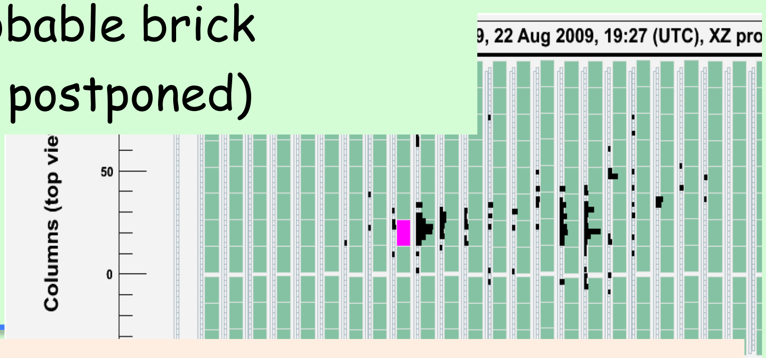
→ ~87% predicted in the bricks

Scanning strategy

Bricks ordered by the probability to contain the neutrino interaction

2008-2009 : analysis of the 1st and 2nd most probable brick

2010-2012 : analysis of the 1st brick (2nd brick postponed)

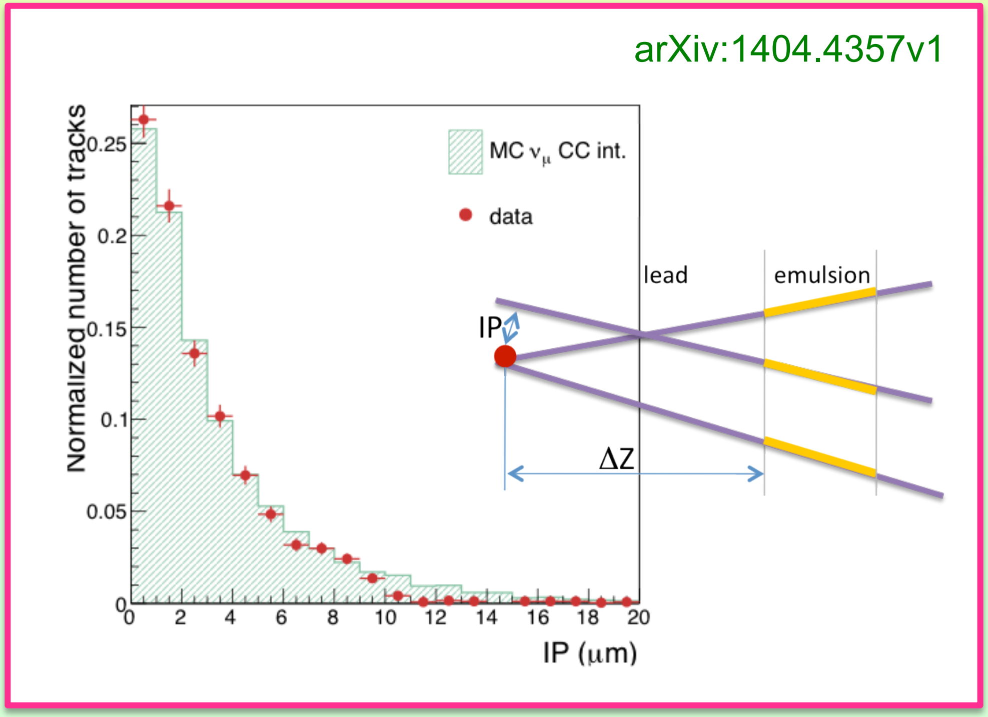


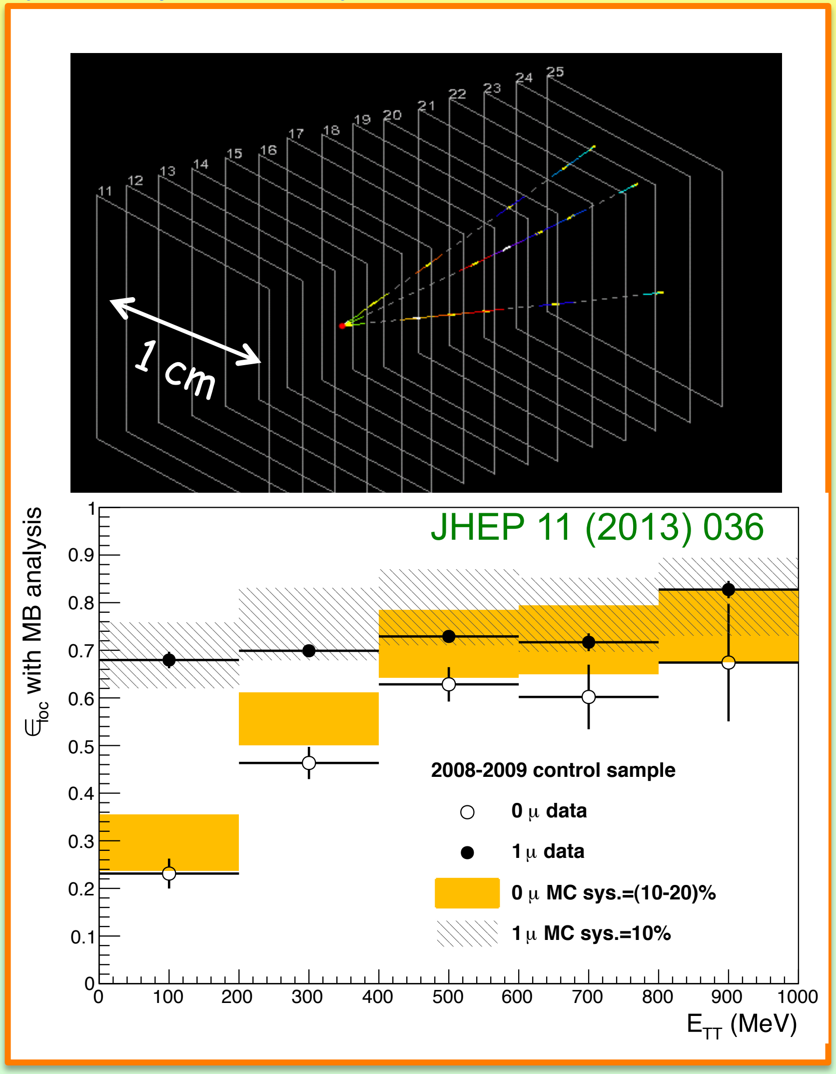
Y.Gornushkin: Poster 113, board 33 Friday session

Vertex location and decay topology Search

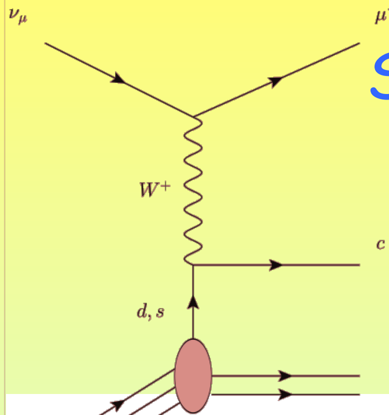
The first two steps of the analysis chain are:

1. location of neutrino interaction
2. search of decay topologies (e.g. large Impact Parameter-IP)





Full MC simulation including all steps of the scanning procedure followed in the scanning labs.



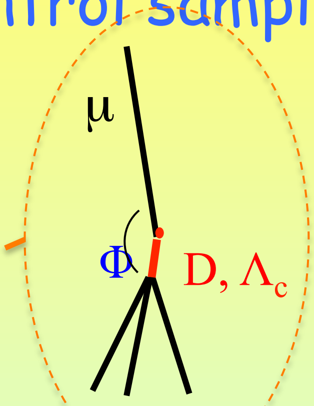
Search for decay topologies: charm control sample

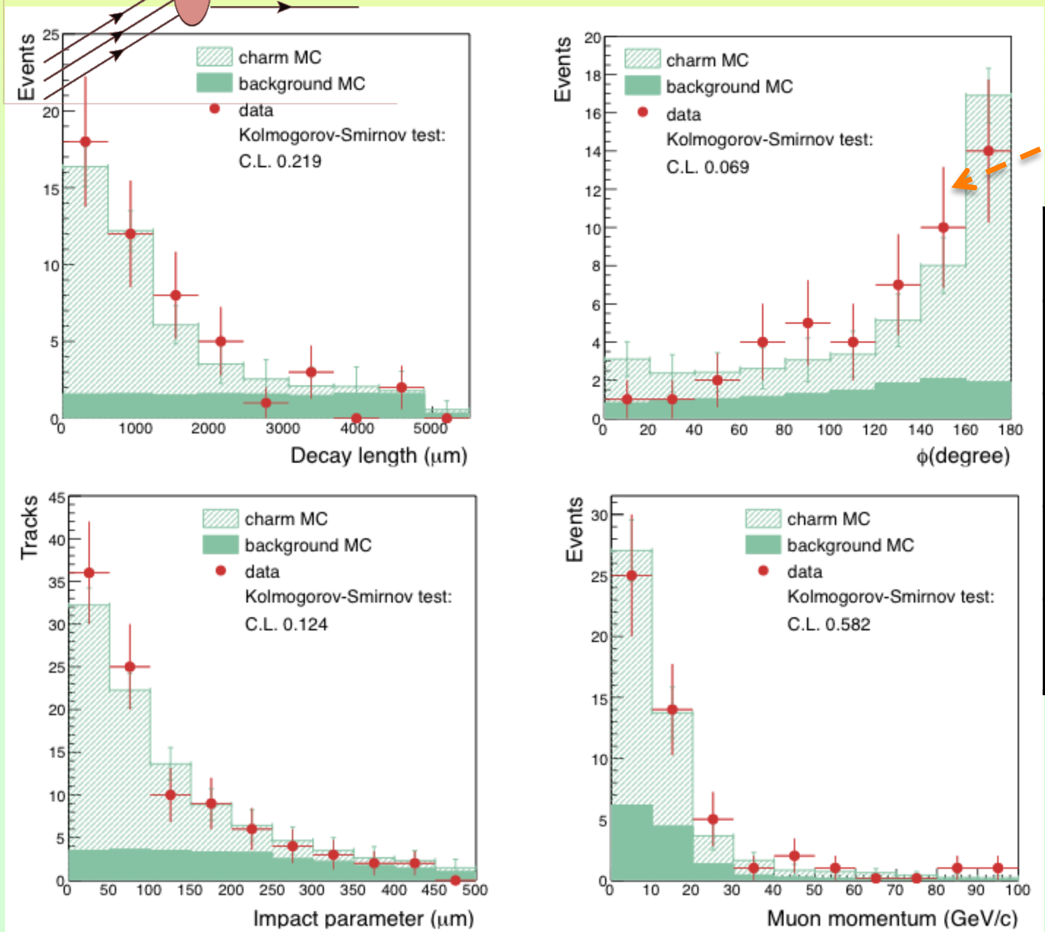
Charmed hadrons produced by ν_μCC interactions

→ muon at the primary vertex,

Mass and lifetime charmed hadrons ~ tau lepton

→ similar decay topology





	charm	back-ground	expected	data
1 prong	21 ± 2	9 ± 3	30 ± 4	19
2 prong	14 ± 1	4 ± 1	18 ± 2	22
3 prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4 prong	0.9 ± 0.2	-	0.9 ± 0.2	4
All	**40±3**	**14±3**	**54±4**	**50**

2008-2010 OPERA data set

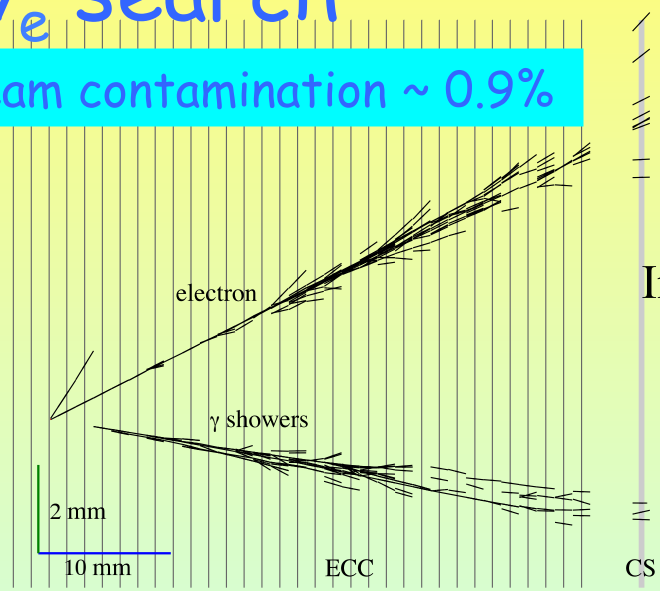
54 ± 4 charm events expected

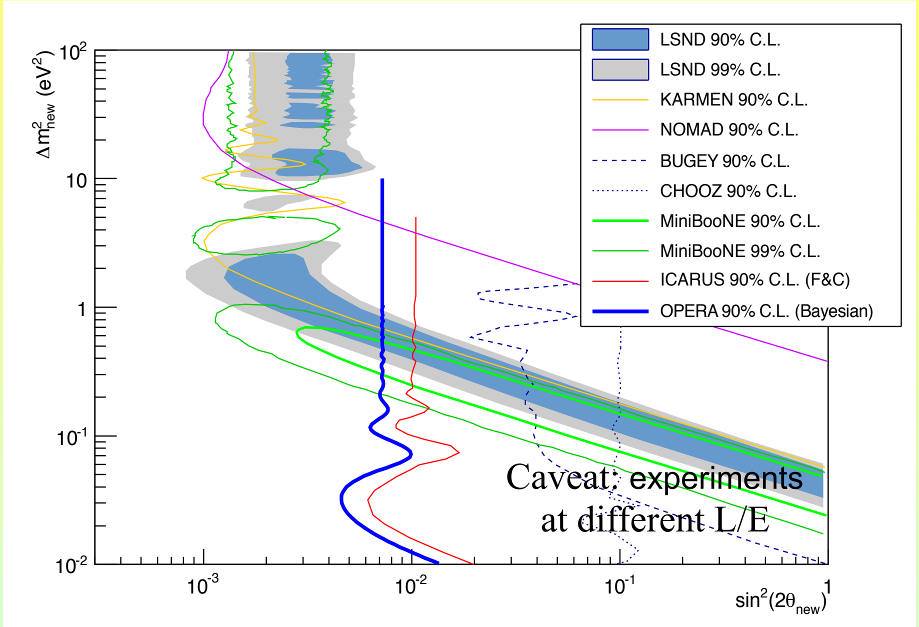
50 observed in control sample

M. Guler: Poster 236, board 48 Tuesday session

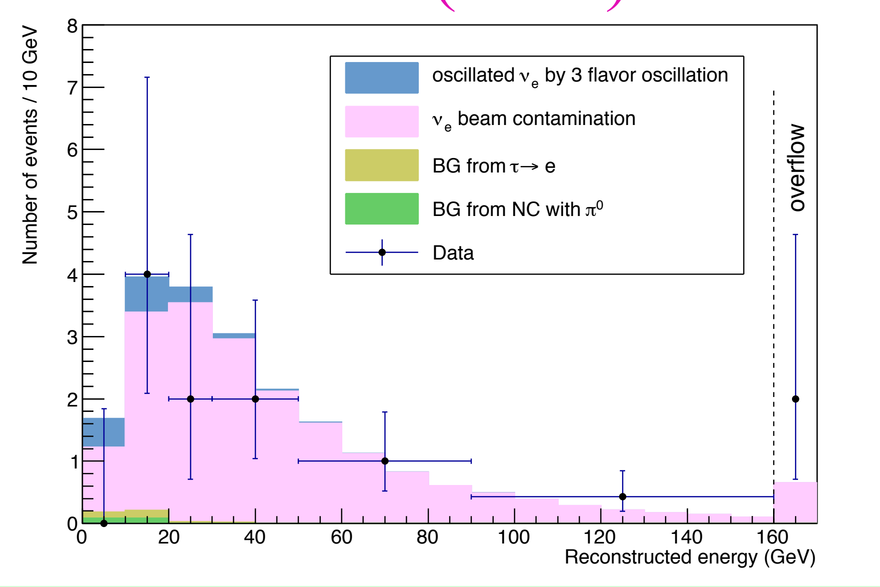
ν_e search

ν_e beam contamination ~ 0.9%





JHEP 1307 (2013) 004



ν_e searched in 505 (~ 50% full statistic) neutrino interaction without the muon in the final state

Extension to full statistic in progress

		E < 20 GeV
Candidate ν_e	19	4
Expected	19.8 ± 2.8 (sys)	4.6

$\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (90% CL)

$\sin^2(2\theta_{13}) < 0.44$ (90% CL)

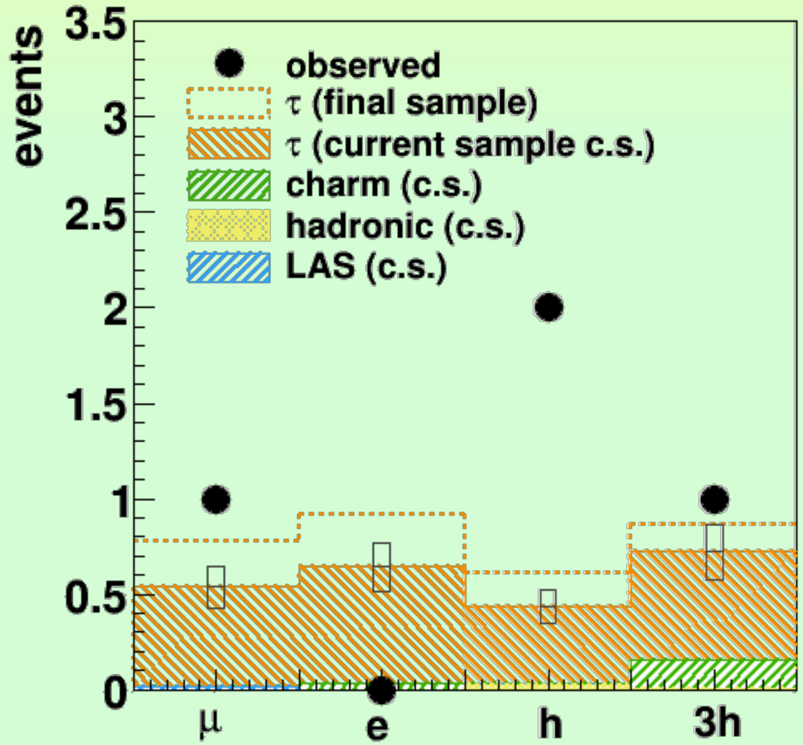
Oscillation results

variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag	No μ or e at the primary vertex			
z_{dec} (μm)	$[44, 2600]$	< 2600	$[44, 2600]$	< 2600
p_T^{miss} (GeV/c)	$< 1^\star$	$< 1^\star$	/	/
ϕ_{lH} (rad)	$> \pi/2^\star$	$> \pi/2^\star$	/	/
p_T^{2ry} (GeV/c)	$> 0.6(0.3)^*$	/	> 0.25	> 0.1
p^{2ry} (GeV/c)	> 2	> 3	> 1 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c^2)	/	> 0.5 and < 2	/	/

Kinematical selection cuts kept fixed since beginning of the experiment.

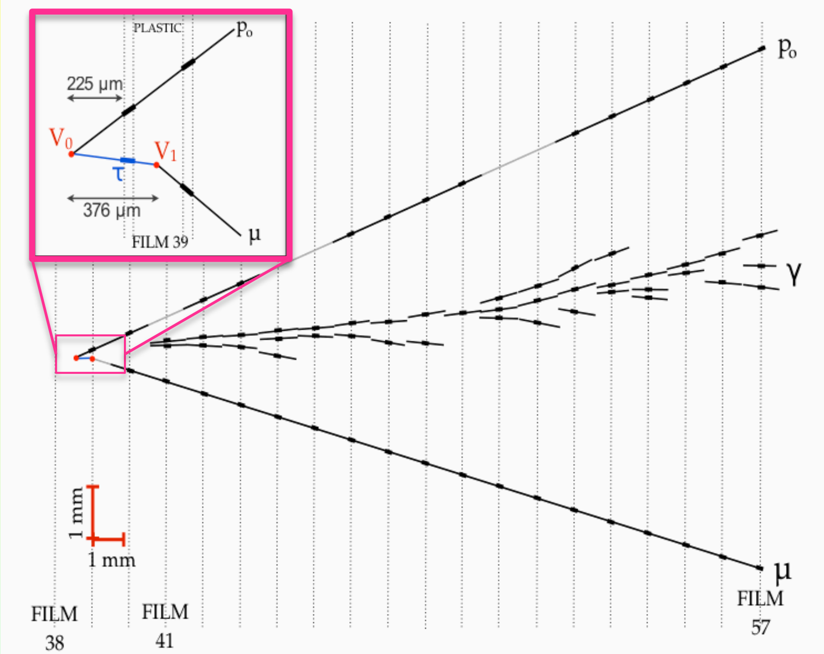
Data sample:
2008/09 : 1st and 2nd probable brick
2010/11/12 : 1st probable brick
5522 events analysed

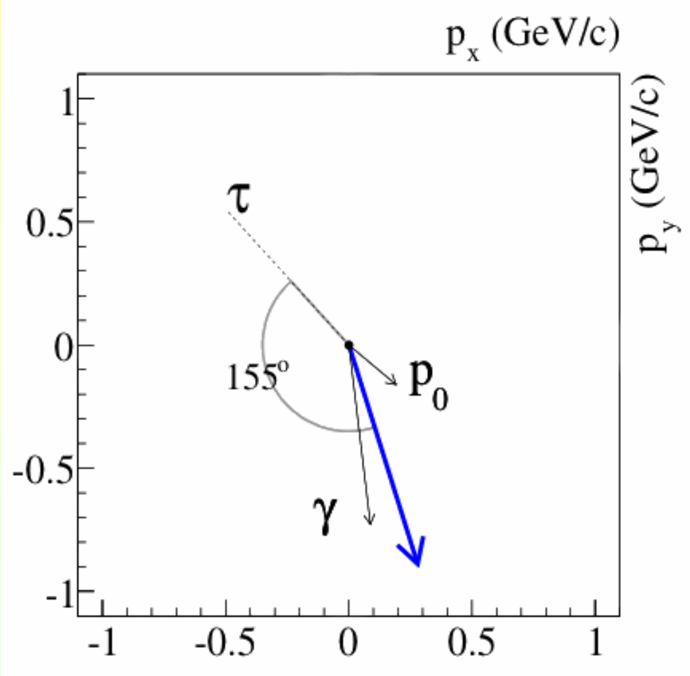
Expected 2.1 ± 0.4
($\Delta m_{23}^2 = 2.32\times10^{-3}eV^2$, $\theta_{23}=\pi/4$)
Observed 4

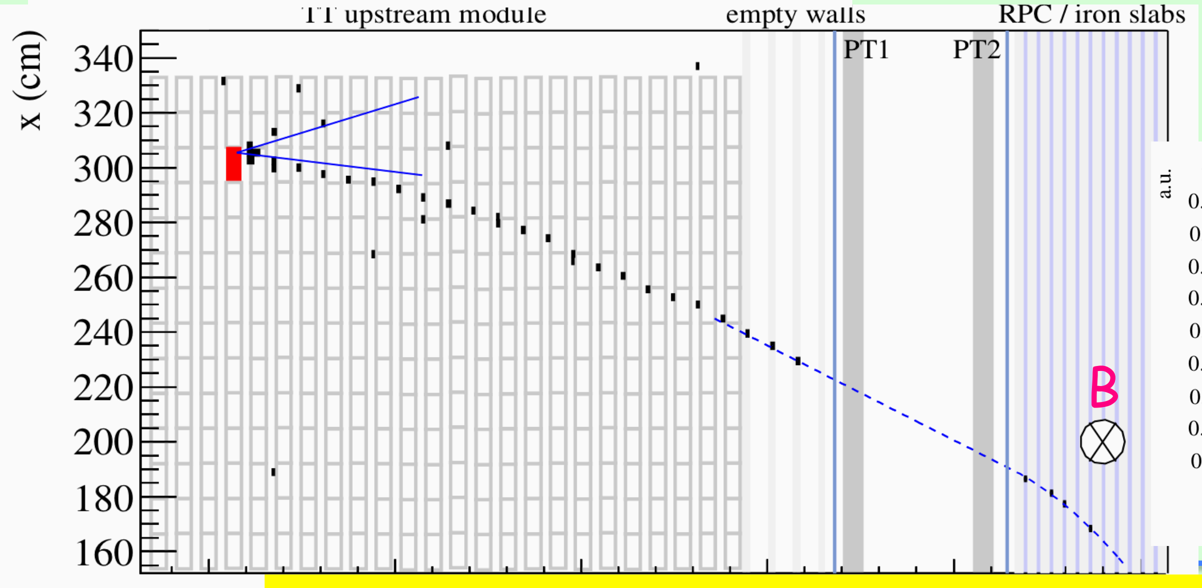


3rd ν_τ candidate $(\tau \rightarrow \mu)$ (2013)

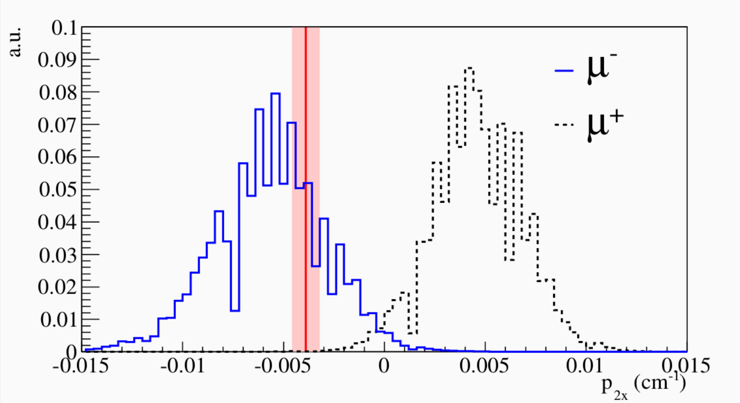
PHYSICAL REVIEW D 89 (2014) 051102(R)





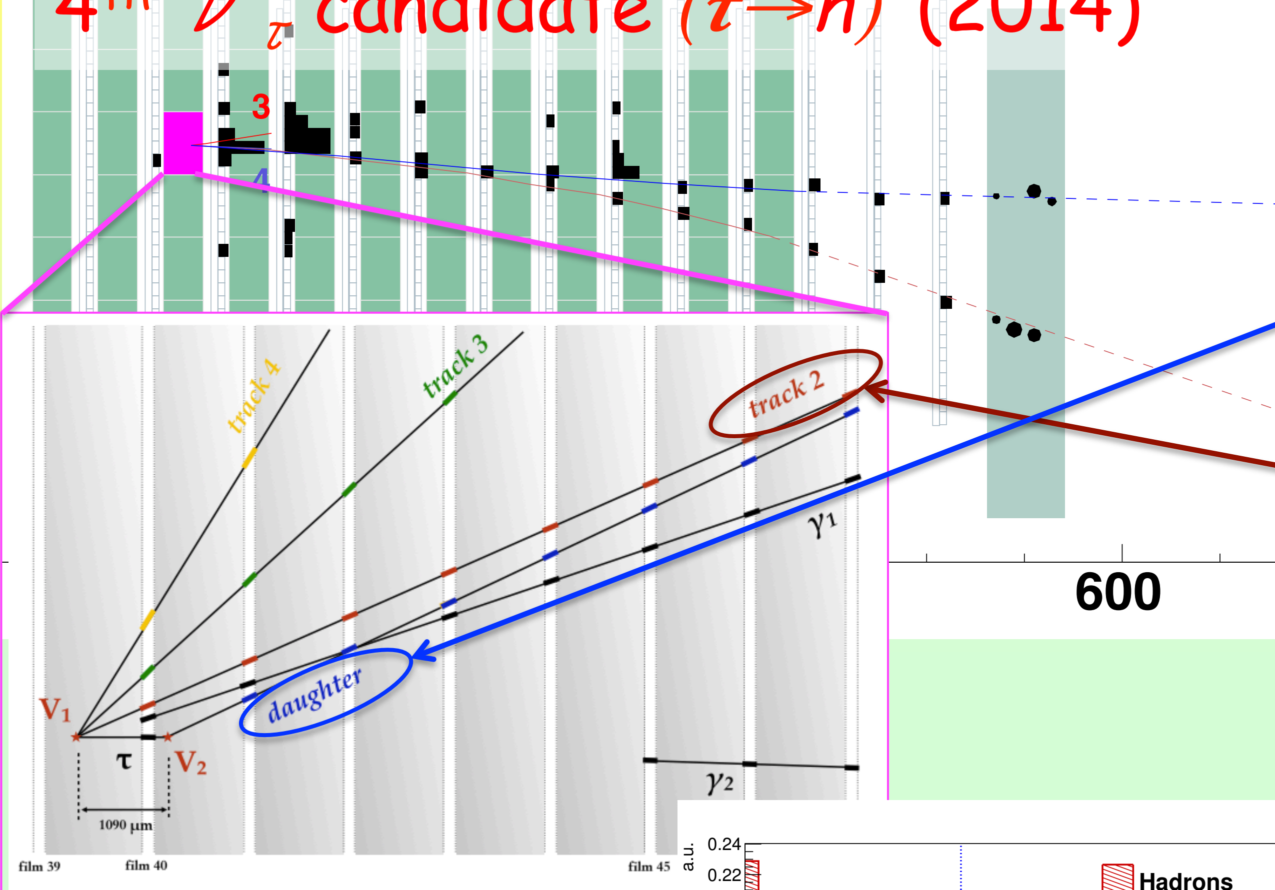


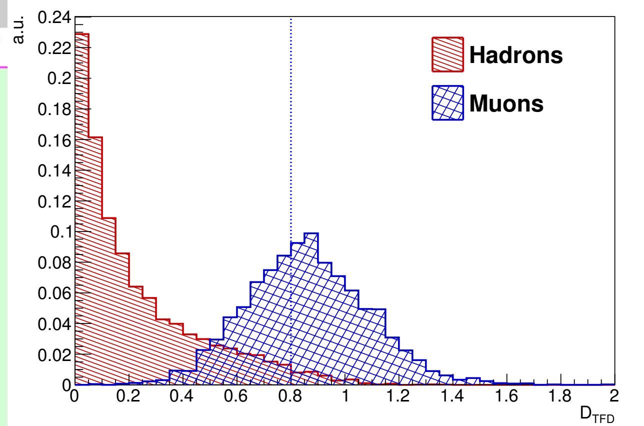
Negative muon measured in the muon spectrometer

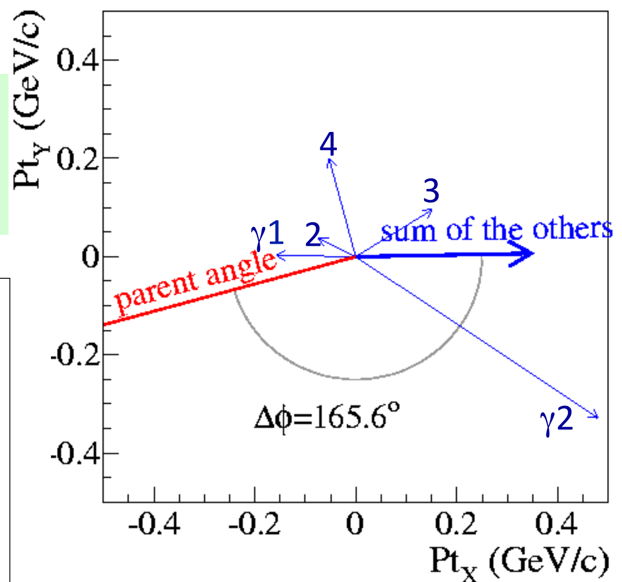


First measurement of the lepton charge in appearance mode

4th ν_τ candidate $(\tau \rightarrow h)$ (2014)

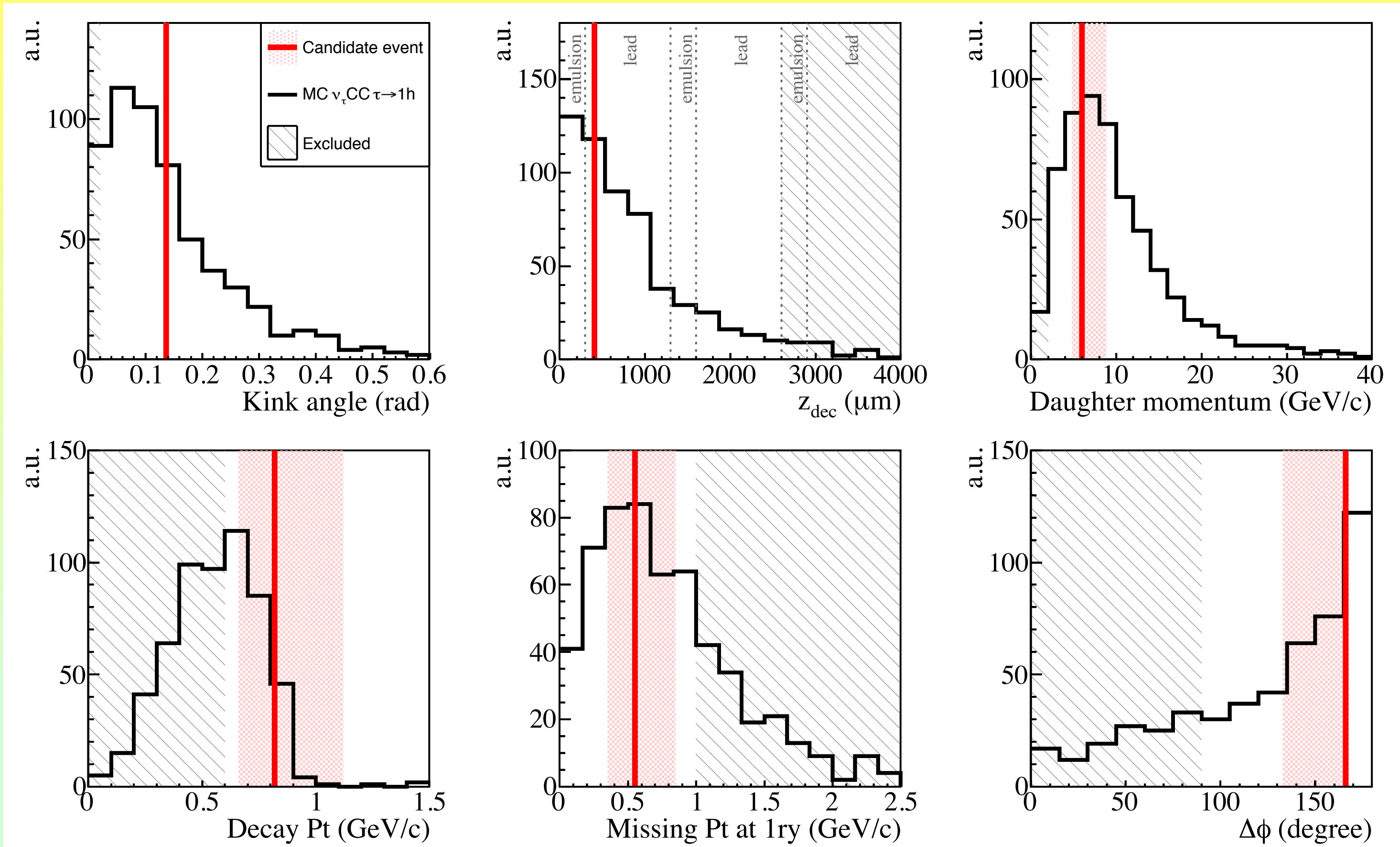






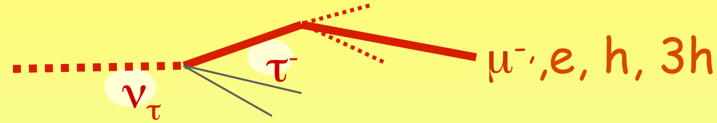
Track 2 from neutrino interaction vertex, p = 1.9 GeV stopping in first iron slab of the magnet

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$



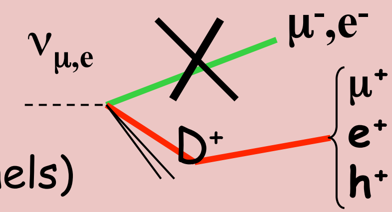
	Values	Selection
P daughter (GeV/c)	$6.0^{+2.2}$	> 2
Kink P_t (GeV/c)	$0.82^{+0.30}$	> 0.6
P_t at 1ry (GeV/c)	$0.55^{+0.30}$	< 1.0
Phi (degrees)	166^{+2}	> 90
Kink angle (mrad)	137 ± 4	> 20
Decay position (μm)	1090 ± 30	< 2600

Kinematics of 3rd ν_τ candidate ($\tau \rightarrow h$)

Background to 

In decreasing order of relevance

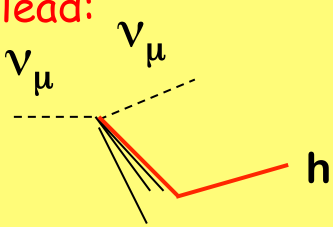
Production of charmed particles in CC interactions (affect all decay channels)



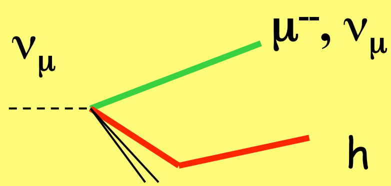
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured charm events in OPERA

Hadronic interactions in lead:

Bck. to $\tau \rightarrow h$



or to $\tau \rightarrow \mu$
(if hadron misid or mismatched with muon)



FLUKA + test beam data (OPERA bricks exposed to pion beams)

Lare angle Coulomb scattering of muons in lead
Bck. to $\tau \rightarrow \mu$

MC tuned on old measurements on lead form factor + dedicated test beam (in progress)

Data sample:

2008/09 : 398 (0μ events) + 1553 (1μ events)

2010/11/12 : 582 (0μ events) + 2153 (1μ events)

The expected signal and background is normalized to the number of located events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{\langle \sigma(\nu_\tau^{CC}) \rangle}{\langle \sigma(\nu_\mu^{CC}) \rangle} \frac{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle}{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle + \alpha \langle \epsilon^{0\mu}(\nu_\tau^{NC}) \rangle} n^{0\mu} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ \mathrm{meV}^2$	Total background	Observed
$\tau \to h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \to \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \to e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

Two statistical method :

- *Fisher combination of single channel p-value*
- *Likelihood ratio*

p-value = 1.03×10^{-5} of no oscillation

no oscillation excluded at 4.2 σ CL

First measurement of Δm^2_{32} with tau appearance

$$N_{\nu_\tau} \propto \int \phi(E) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \epsilon(E)\sigma(E) dE$$

$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$$

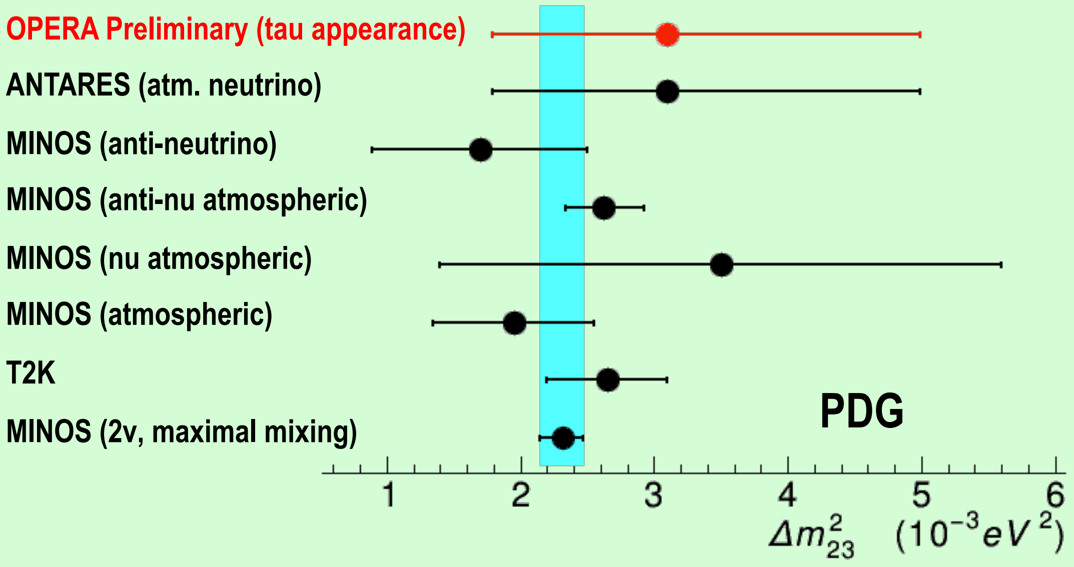
OPERA Off-peak
L/<E> ~ 43 Km/GeV
$(L/\langle E\rangle)_{peak}$ ~ 500 Km/GeV

strong dependence on Δm^2 → measure Δm^2 with counting experiment

90% CL intervals on Δm^2_{32} assuming $\sin2(2\theta_{23}) = 1$

Feldman&Cousin
$[1.8 - 5] \times 10^{-3}$ eV^2

Bayesian
$[1.9 - 5] \times 10^{-3}$ eV^2



Sterile neutrinos

Tau appearance in the presence of sterile neutrino (3+1)

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$$

Solar driven oscillation neglected $\Delta_{21} \sim 0$

~ standard oscillation

pure exotic oscillation

$$P_{\nu_\mu \to \nu_\tau} = 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2}$$

interference terms

$$+2\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin \Delta_{41}$$

$$-4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$

$$+8\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$

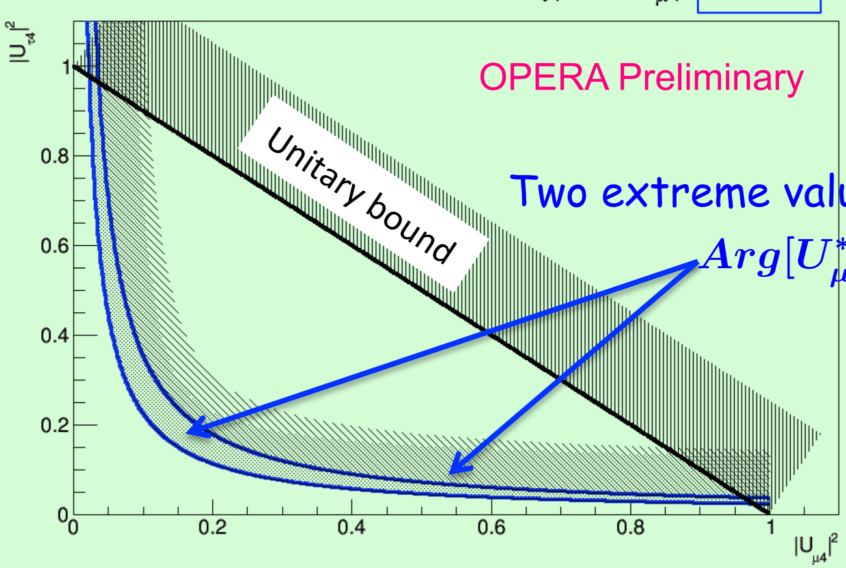
$$+4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

Normal hierarchy

Profile likelihood using Tau rate only

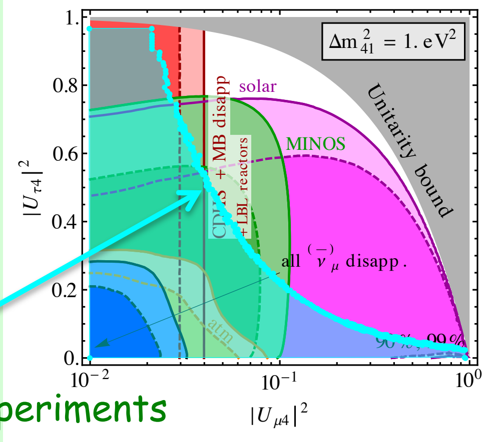
$$\Delta m^2_{32} = 2.32 \times 10^{-3} eV^2$$

90% CL bounds on $U_{\tau 4}$ and $U_{\mu 4}$



Two extreme values ($\pi/2$, $3\pi/2$) of $Arg[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}]$

Complementary measurement wrt disappearance experiments



Kopp et al. JHEP 1305 (2013) 050

Choosing a particular representation (same as MINOS)

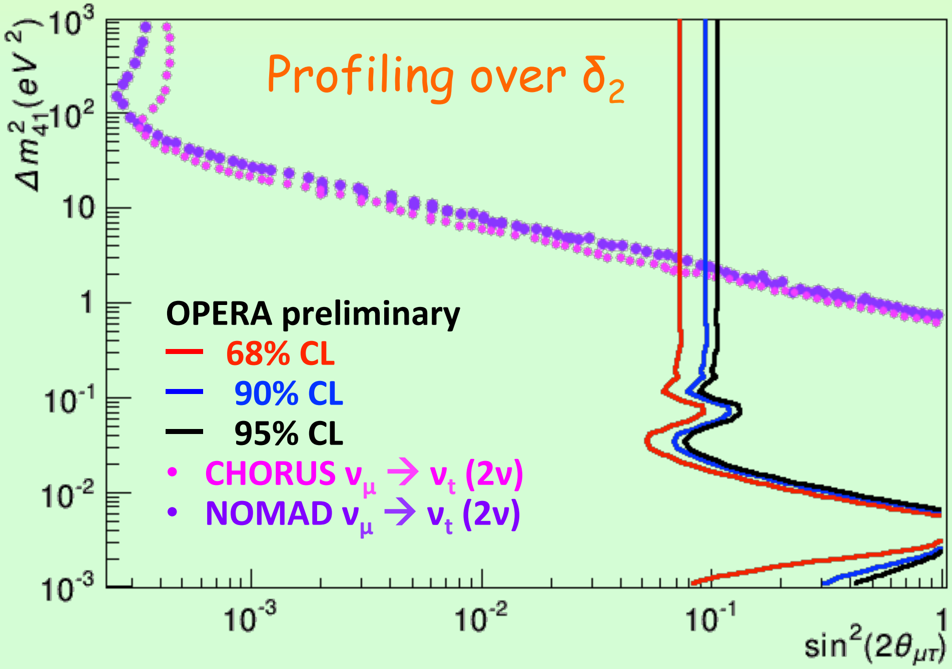
$\Delta_{21} \sim 0$ (solar oscillation)
$s_{14} \sim 0$ (reactor anomaly)
$\rightarrow \delta_1 = 0$

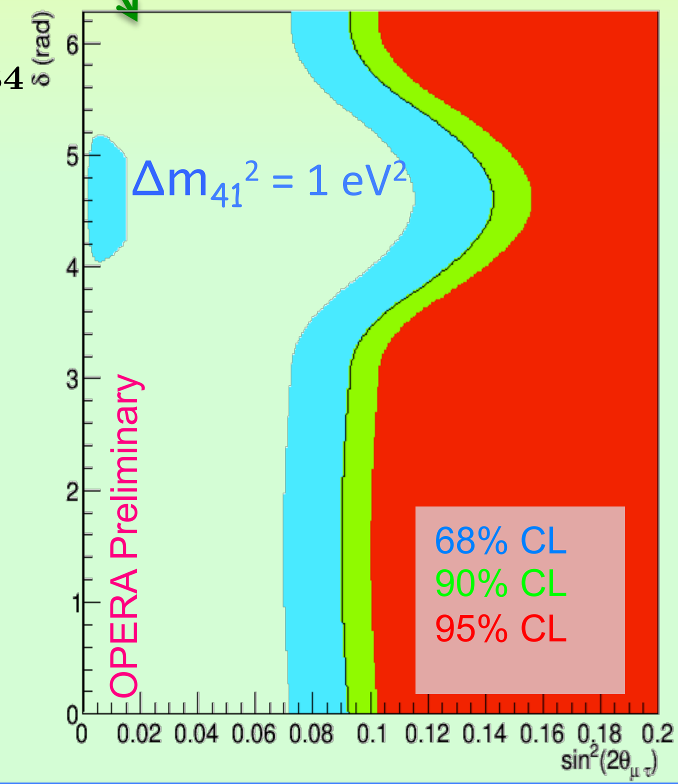
$$U = R_{34}(\theta_{34}) R_{24}(\theta_{24,\delta_2}) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_1) R_{12}(\theta_{12}, \delta_3)$$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & c_{14}s_{13}e^{-i\delta_1} & s_{14} \\ U_{\mu 1} & U_{\mu 2} & -s_{14}s_{13}e^{-i\delta_1}s_{24}e^{-i\delta_2} + c_{13}s_{23}c_{24} & c_{14}s_{24}e^{-i\delta_2} \\ U_{\tau 1} & U_{\tau 2} & -s_{14}c_{24}s_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}s_{34}s_{24}e^{i\delta_2} + c_{13}c_{23}c_{34} & c_{14}c_{24}s_{34} \\ U_{s1} & U_{s2} & -s_{14}c_{24}c_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}c_{34}s_{24}e^{i\delta_2} - c_{13}c_{23}s_{34} & c_{14}c_{24}c_{34} \end{bmatrix}$$

Effective mixing

$$\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 = \sin^2 2\theta_{24} \sin^2 \theta_{34}$$





Conclusions

- OPERA has recorded neutrino interaction equivalent to ~1.8 x 10^{20} pot delivered by CNGS beam from 2008 to 2012 (80% of nominal)
- 4 ν_τ candidates observed so far with a background of 0.23 event.
- No oscillation hypothesis excluded at 4.2 σ

Observation of ν_τ *appearance*

- First measurement of Δm^2_{31} = [1.8 – 5.0] x 10^{-3} eV^2 (90% CL) for $\sin^2(2\theta_{23}) = 1$ using neutrino appearance
- Constrain on sterile neutrinos: first limits on $|U_{\mu 4}|^2$ $|U_{\tau 4}|^2$ from direct measurement of $\nu_\mu \rightarrow \nu_\tau$ oscillation

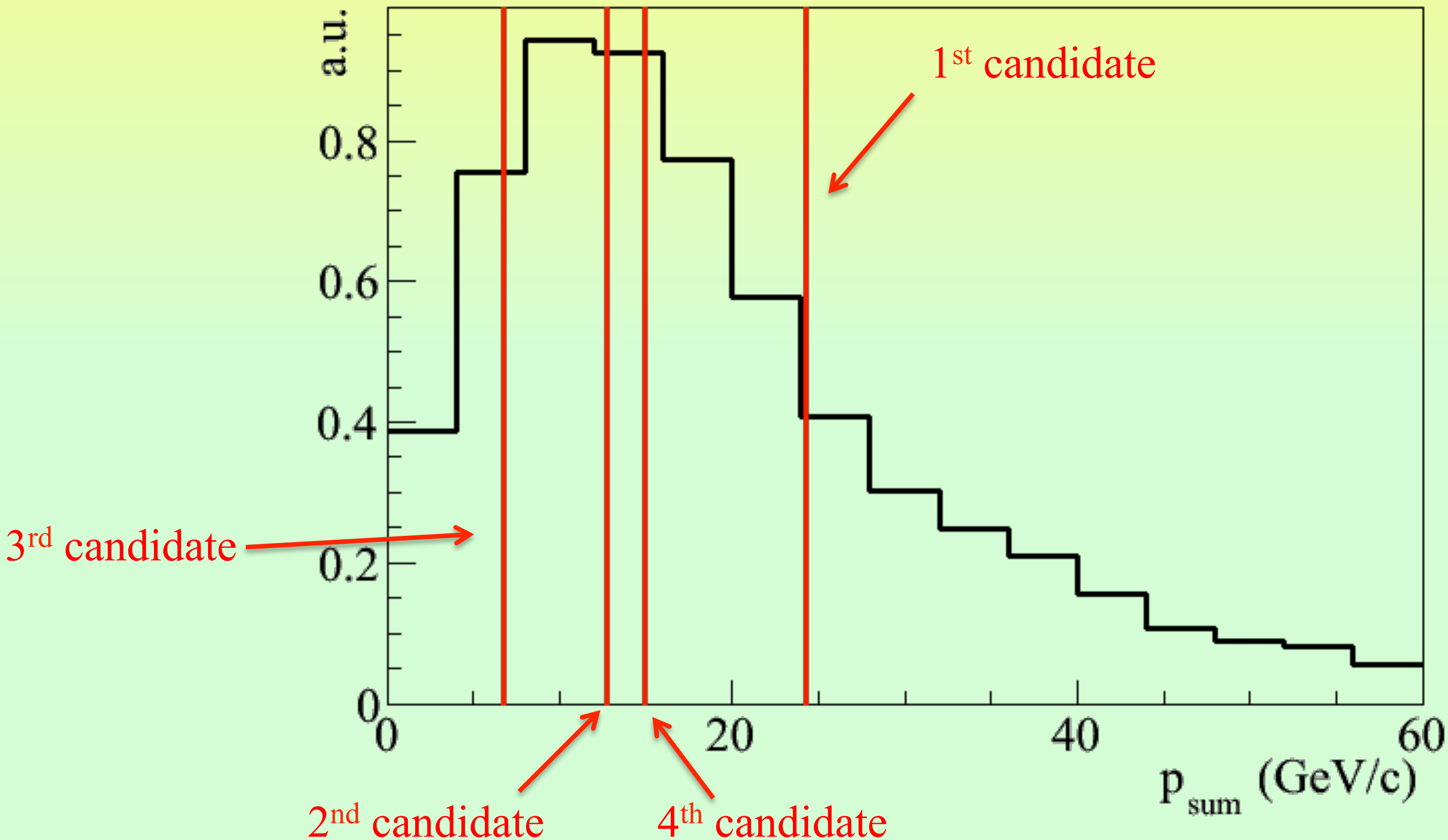
Thank you for your attention

Image taken using OPERA emulsion film with pinhole hand made camera courtesy by D.onato Di Ferdinando (INFN –Bologna)

Backup

Visible energy of all the candidates

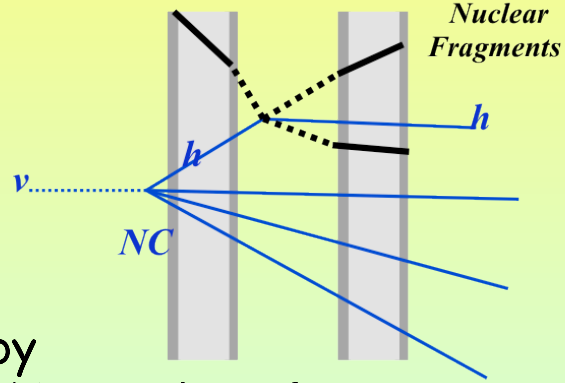
Sum of the momenta of charged particles and γ's measured in emulsion

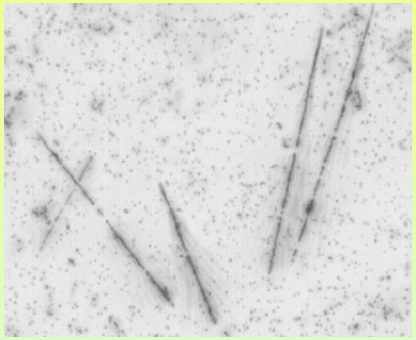


Hadron interaction background

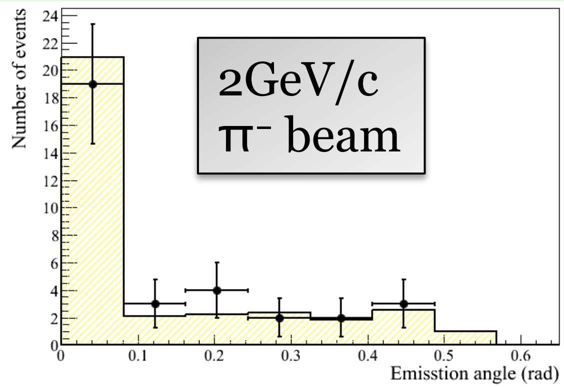
Estimated with Fluka MC and validated with test beam data (OPERA bricks exposed to pion beams)

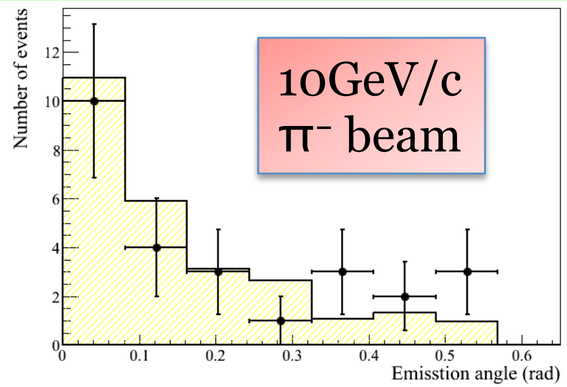
Background to
$\tau \rightarrow h$ = 3.09 x 10^{-5} / located events
$\tau \rightarrow 3h$ = 1.5 x 10^{-5} / located events

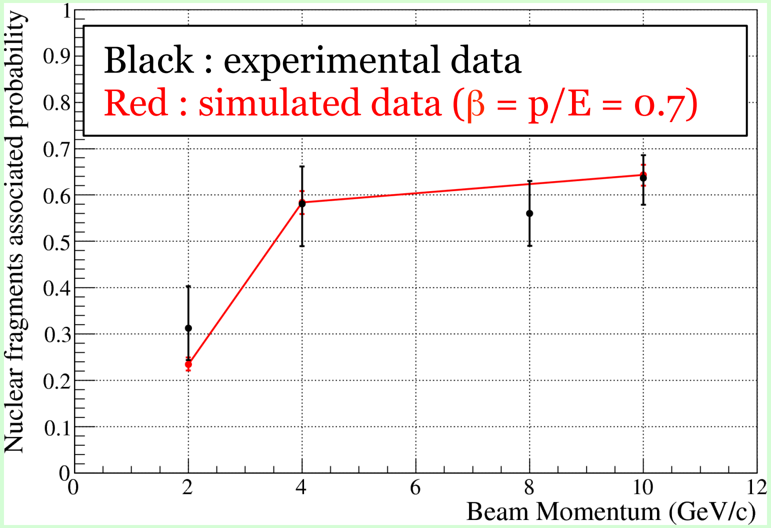




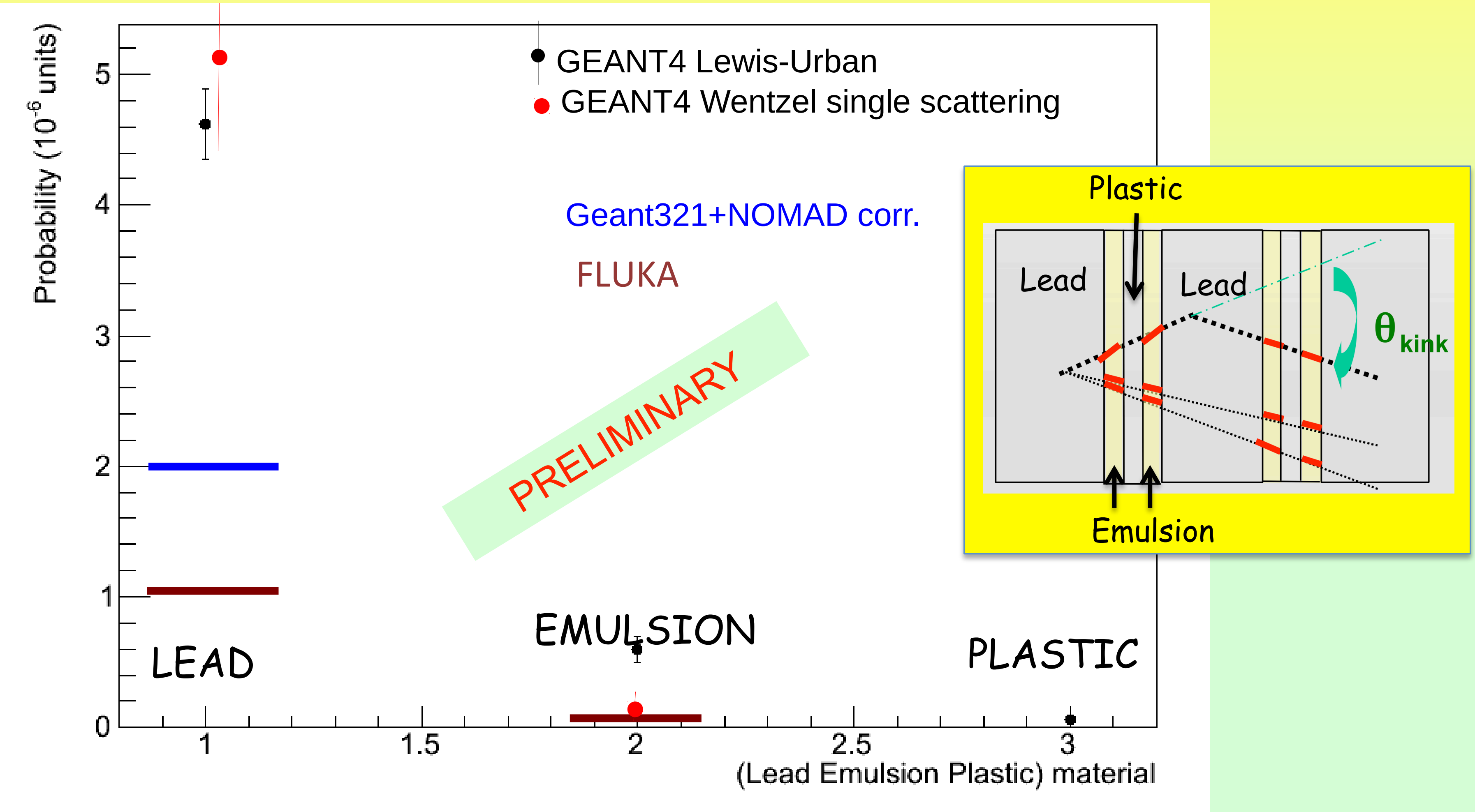
Hadron interaction rate suppressed by search of large angle tracks produced by nuclear fragments





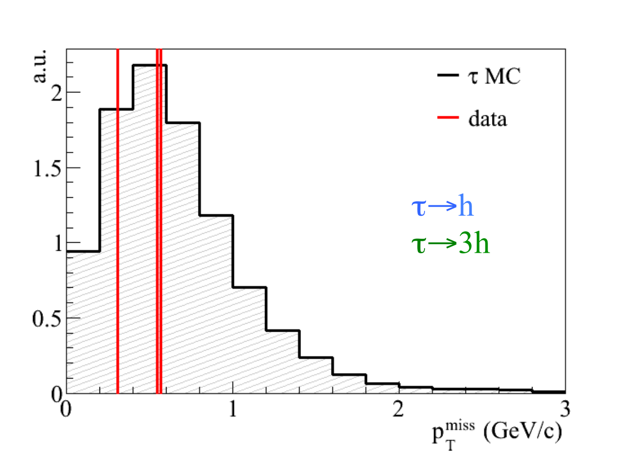


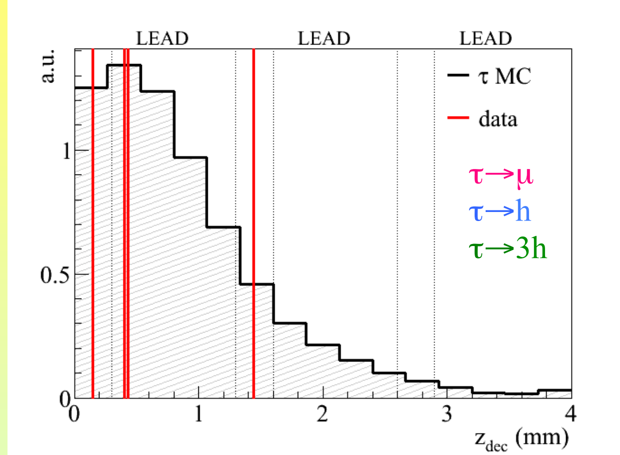
Large angle muon scattering background

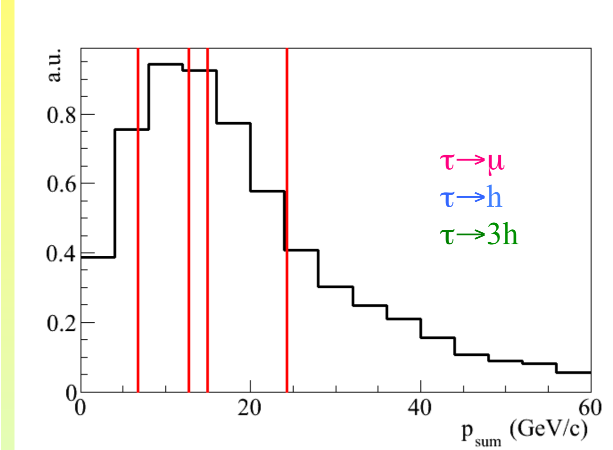


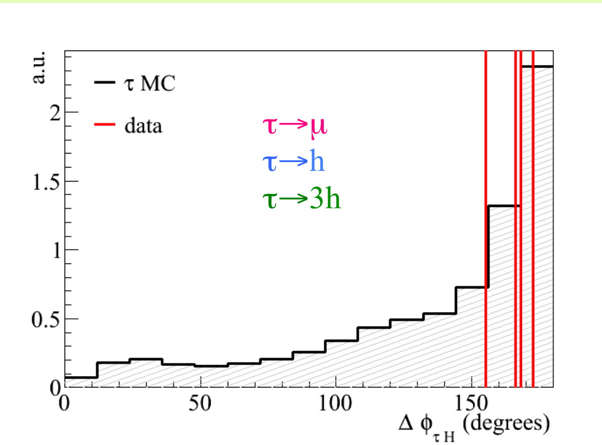
No measurements except an upper limit from scattering on Cu: S.A. Akimenko et al., NIM A243 (1986) 518 (< 10^{-5} in lead). 10^{-5} rate used

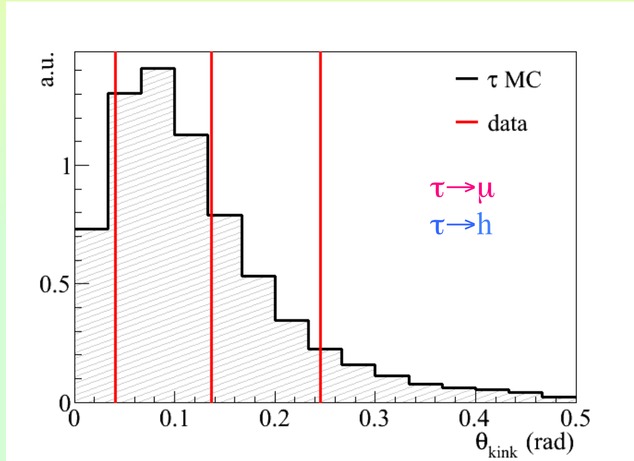
Plan to revise this number by an experimental measurement with emulsion

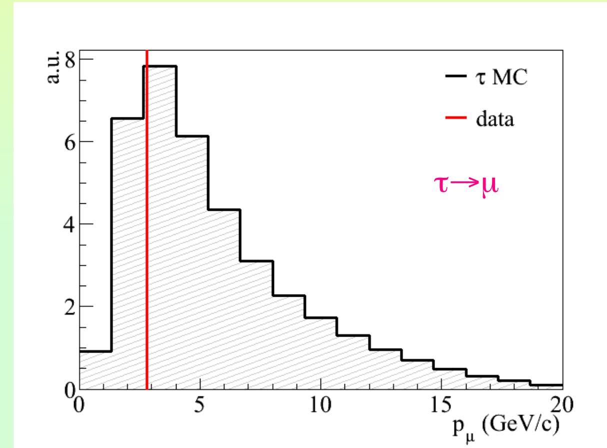

a.u.
τ MC
data
τ→h
τ→3h
p_T^{miss} (GeV/c)

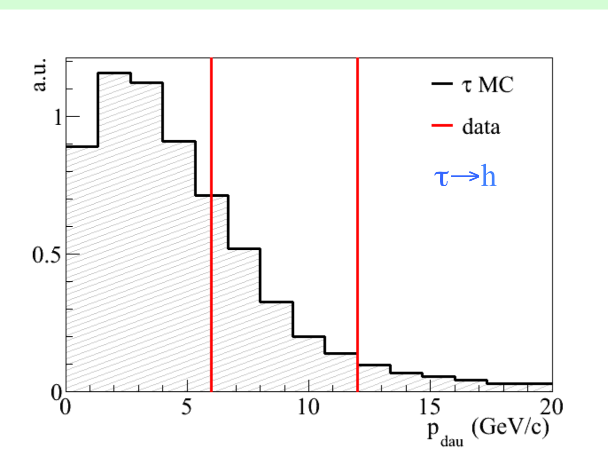

LEAD
LEAD
LEAD
a.u.
τ MC
data
τ→μ
τ→h
τ→3h
z_{dec} (mm)

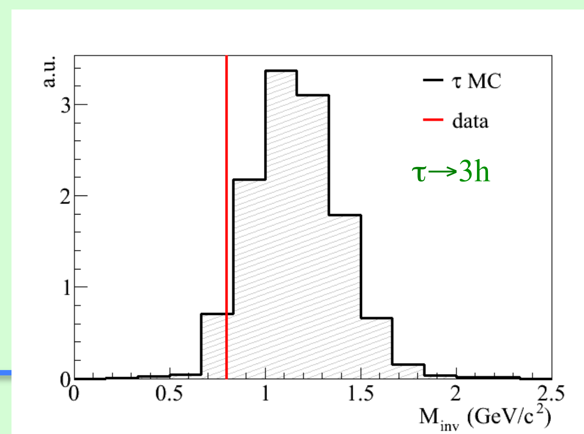

a.u.
τ→μ
τ→h
τ→3h
p_{sum} (GeV/c)

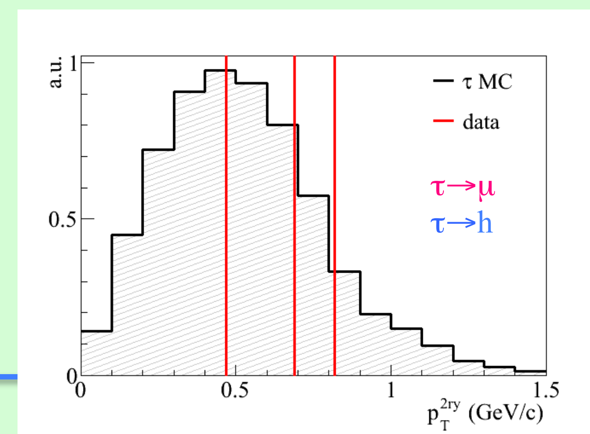

a.u.
τ MC
data
τ→μ
τ→h
τ→3h
$\Delta\phi_{\tau H}$ (degrees)


a.u.
τ MC
data
τ→μ
τ→h
θ_{kink} (rad)


a.u.
τ MC
data
τ→μ
p_μ (GeV/c)


a.u.
τ MC
data
τ→h
p_{dau} (GeV/c)


a.u.
τ MC
data
τ→3h
M_{inv} (GeV/c^2)


a.u.
τ MC
data
τ→μ
τ→h
p_T^{2ry} (GeV/c)

Track features

			First measurement	Second measurement	Average	
	Track ID	Particle ID	Slopes	Slopes	**Slopes**	**P (GeV/c)**
1ry	1 parent	τ	-0.143, 0.026	-0.145, 0.014	**-0.144, 0.020**	**-**
	2	Hadron (Range)	-0.044, 0.082	-0.047, 0.073	**-0.046, 0.078**	**1.9 [1.7, 2.2]**
	3	Hadron (interact)	0.122, 0.149	0.139, 0.143	**0.131, 0.146**	**1.1 [1.0, 1.2]**
	4	proton	-0.083, 0.348	-0.080, 0.355	**-0.082, 0.352**	**0.7 [0.6, 0.8]** $p\beta$ = 0.4 [0.3, 0.5]
	γ1	e-pair	-0.229, 0.068	-0.238, 0.055	**-0.234, 0.062**	**0.7 [0.6, 0.9]**
	γ2	e-pair	0.111, -0.014	0.115,-0.034	**0.113,-0.024**	**4.0 [2.6, 8.7]**
2ry	daughter	Hadron (Range)	-0.084, 0.148	-0.091, 0.145	**-0.088, 0.147**	**6.0 [4.8, 8.2]**

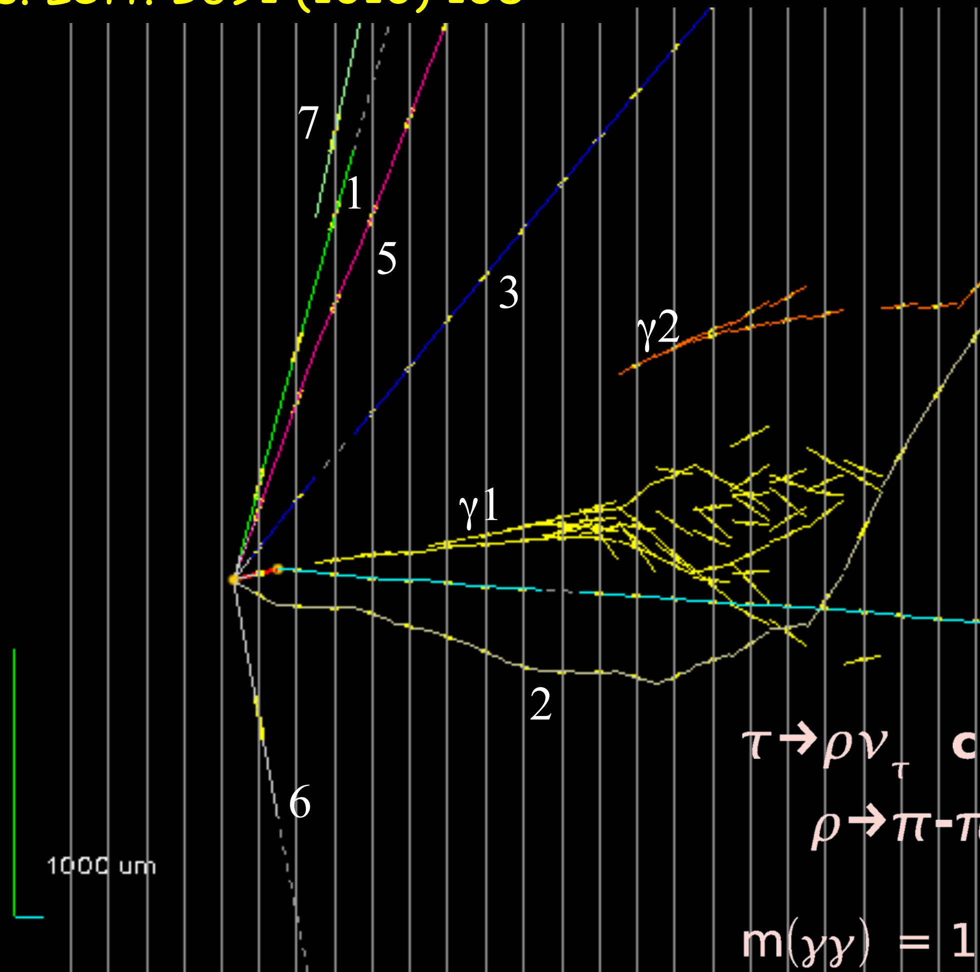
		ΔZ (μm)	**$\delta\theta_{RM}$ (mrad)**	**IP (μm)**	**IP Resolution (μm)**	**Attachment**
γ1	To 1ry	676	21.9	**2**	**8**	**OK**
γ2	To 1ry	7176	9.2	**33**	**43**	**OK**
	To 2ry	6124	9.2	**267**	**36**	**Excluded**

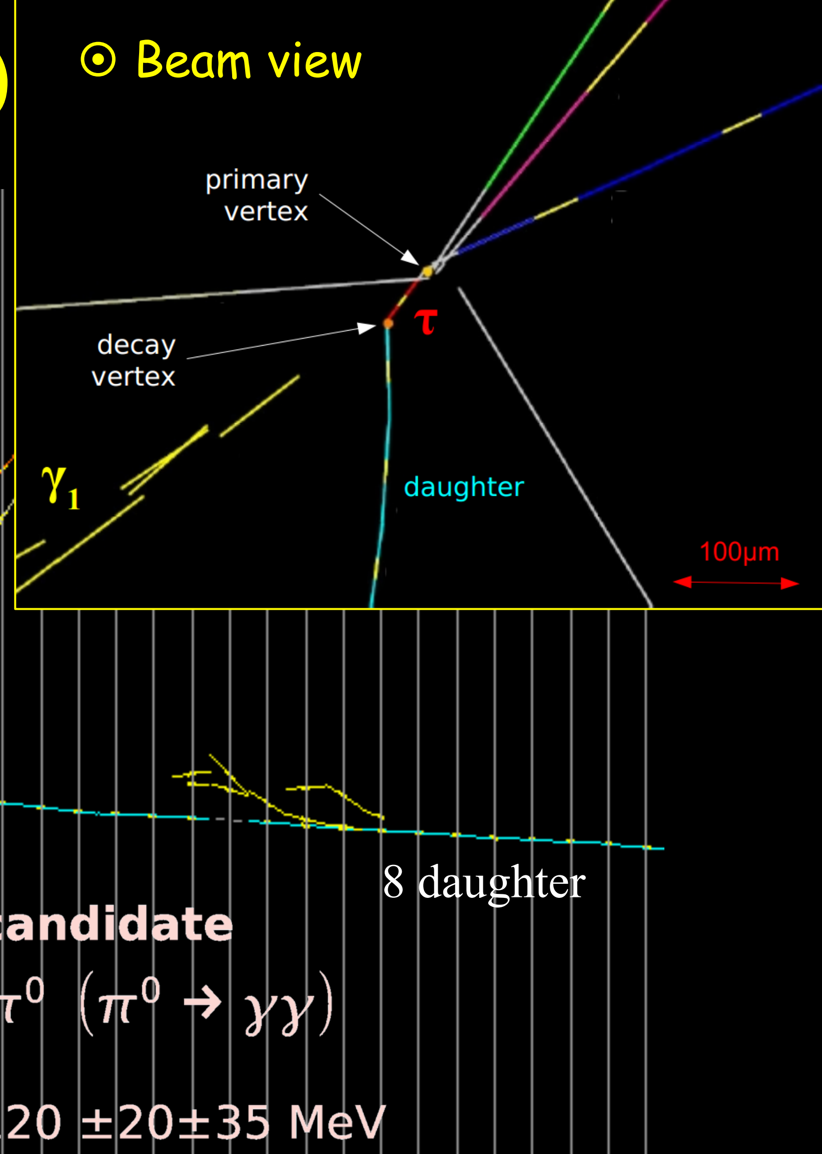
$$M = 0.59^{+0.20}_{-0.15}\ \mathrm{GeV/c^2}$$

Not a single π^0

1st ν_τ candidate $(\tau \rightarrow h)$ (2010)

Phys. Lett. B691 (1010) 138





$\tau \rightarrow \rho \nu_\tau$ **candidate**

$\rho \rightarrow \pi^- \pi^0 \ (\pi^0 \rightarrow \gamma\gamma)$

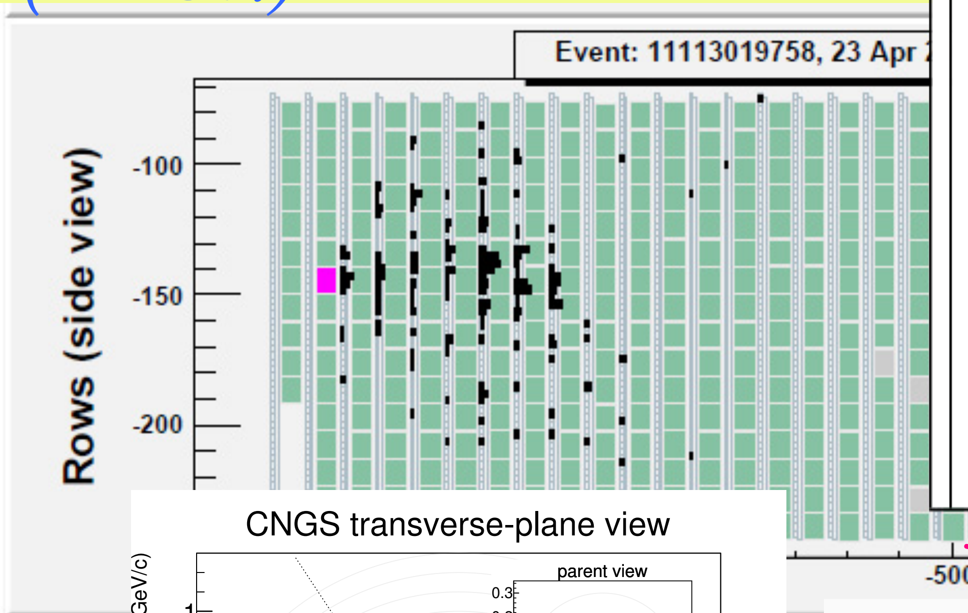
$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

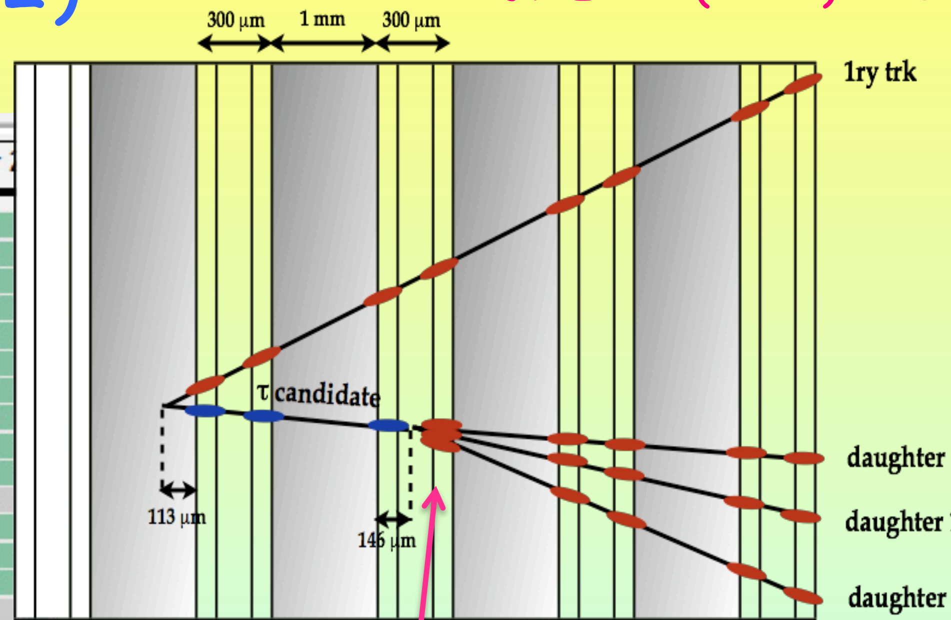
$m(\pi^- \gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

$Br(\tau \rightarrow \rho \nu_\tau) \sim 25\%$

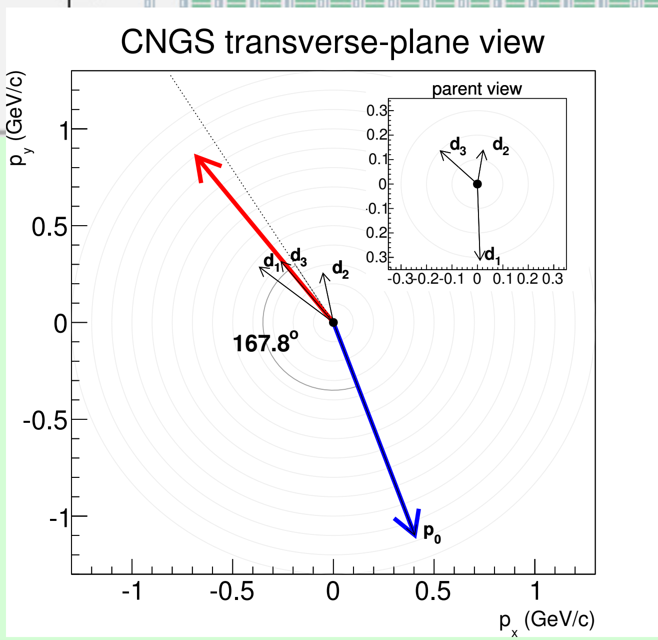
2nd ν_τ candidate (2012) ($\tau \rightarrow 3h$)

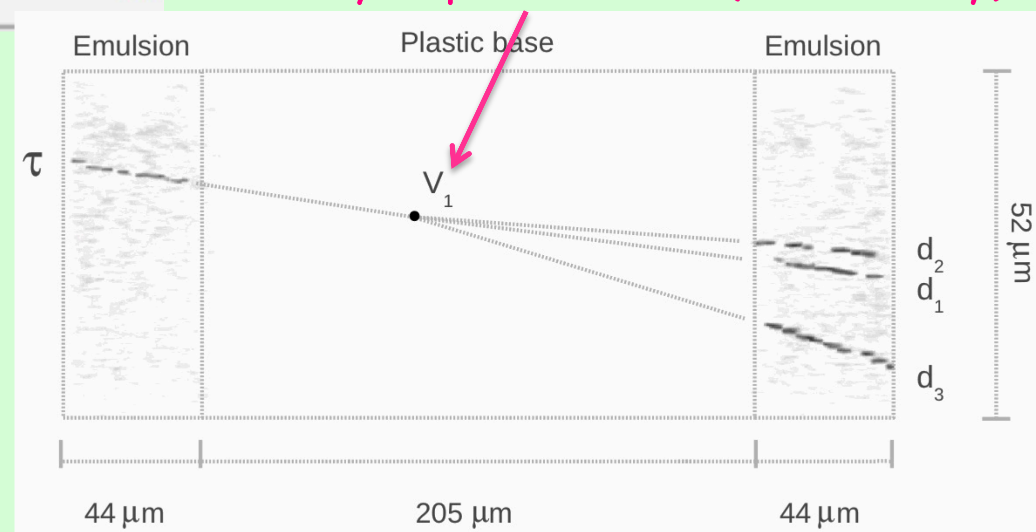
JHEP 11 (2013) 036



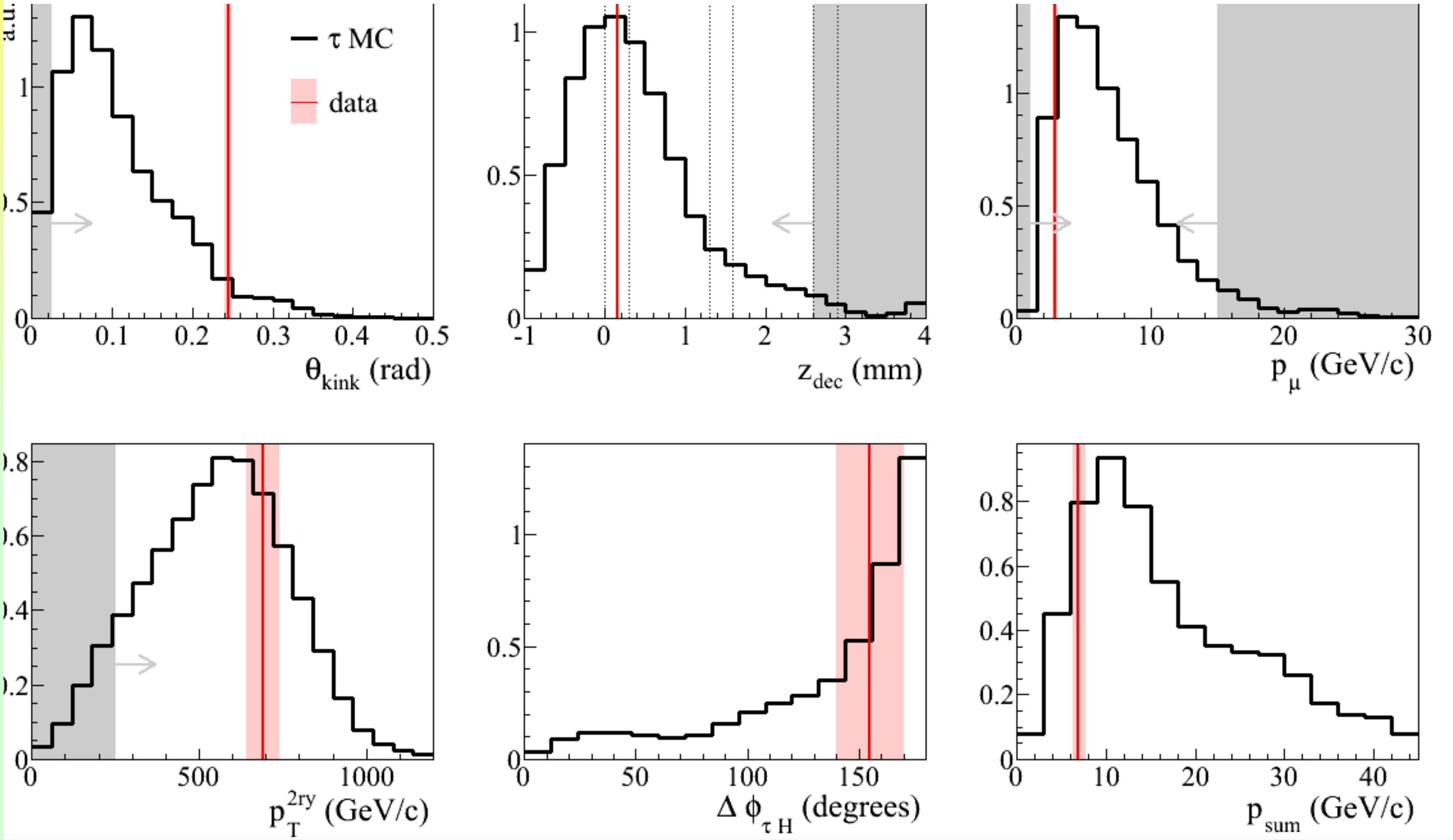


Tau decay in plastic base (low density)





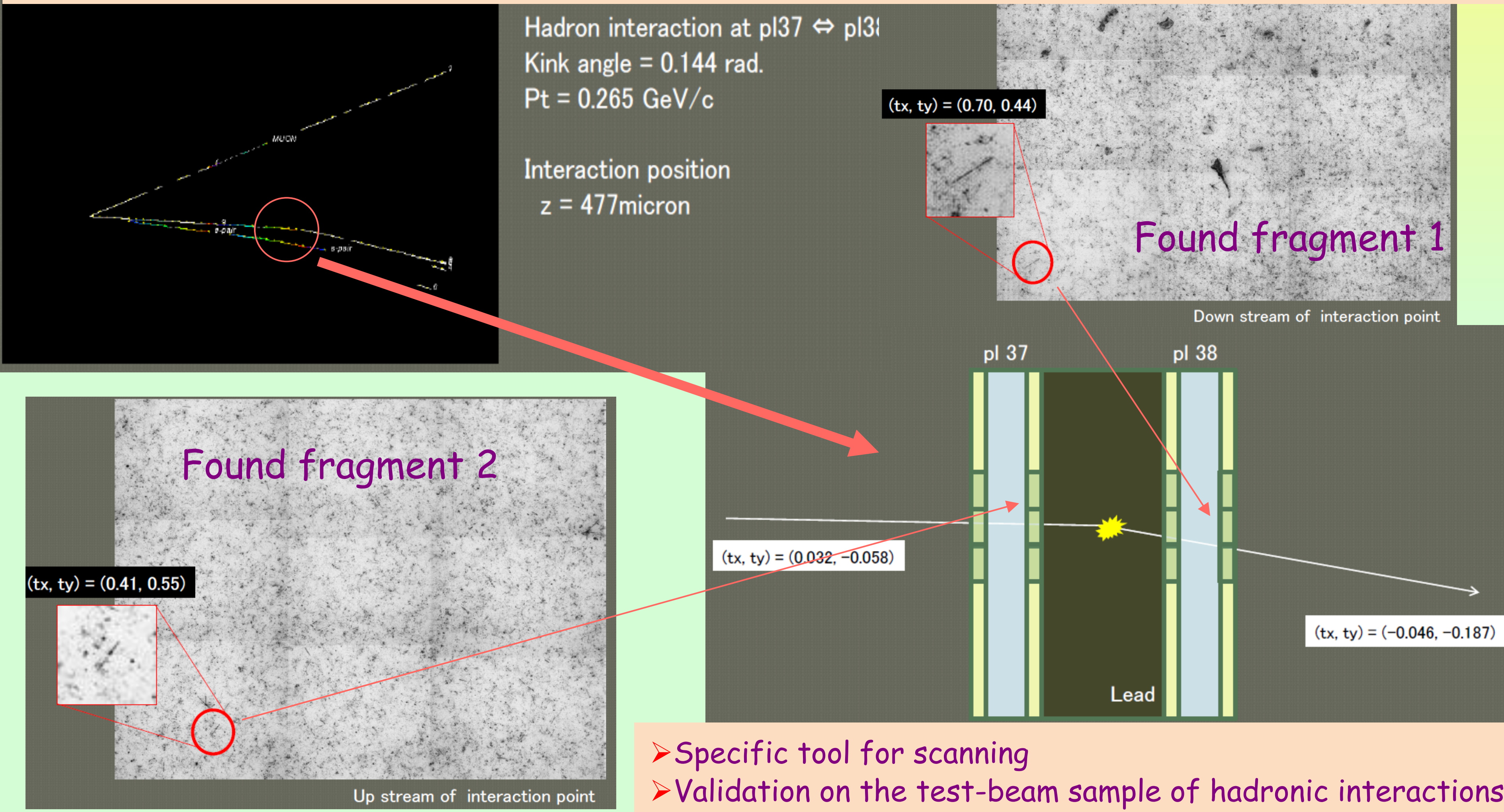
Kinematics of 3rd ν_τ candidate ($\tau \to \mu$)



		Pμ (GeV/c)	2.8±0.2
Kink angle (mrad)	245 ± 5	Pt (MeV/c)	690±50
decay length (μm)	376 ± 10	φ (degrees)	154.5 ± 1.5

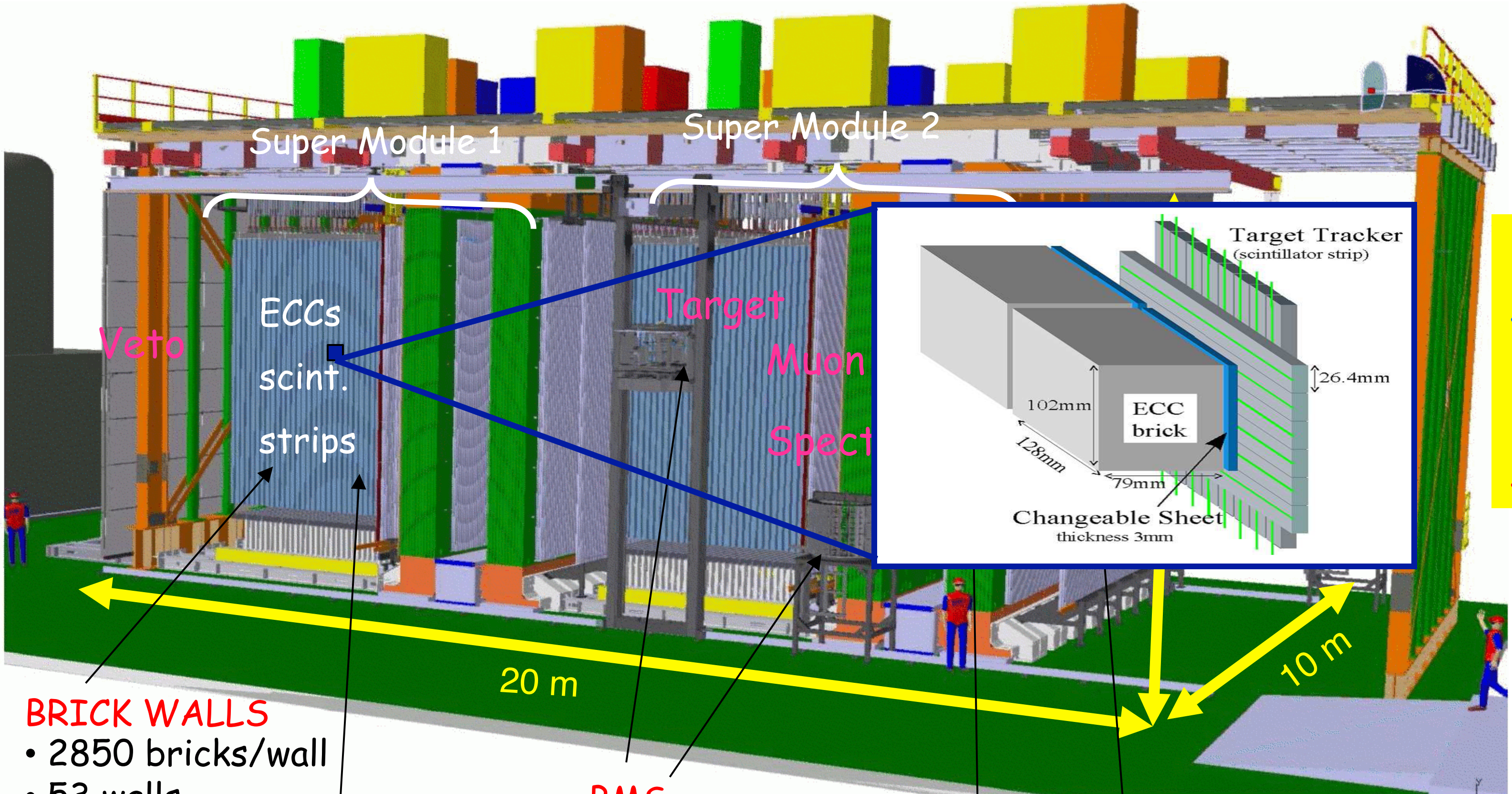
Search for highly ionizing particles in hadron interactions

Hadron interactions background can be reduced by increasing the detection efficiency of protons and nuclear fragments emitted in the cascade of intra-nuclear interactions and in nuclear evaporation process



- Specific tool for scanning
- Validation on the test-beam sample of hadronic interactions
- No highly ionizing particle found in OPERA ν_τ candidate

Oscillation Project with Emulsion tRacking Apparatus



Detector supermodules construction: Sept. 2003 - spring 2007

BRICK WALLS
- 2850 bricks/wall
- 53 walls

TARGET TRACKERS
- 2x31 scintill. strips walls
- 256+256 X-Y strips/wall
- WLS fiber readout
- 64-channel PMTs
- 63488 channels
- 0.8 cm resol., ε 99%
- rate 20 Hz/pixel @1 p.e.

Target Trackers
- neutrino trigger
- brick localization

BMS
Brick
Manipulator
system

HIGH PRECISION TRACKERS
6 drift-tube layers/spectrometer
spatial resolution < 0.5 mm

INNER TRACKERS
- 990-ton dipole magnets (B= 1.55 T) instrumented with 22 RPC planes
- 3050 m^2, ~1.3 cm res.

RPC + drift tubes in spectrometers:
- muon ID,
- momentum,
- charge